

SPEED LIMIT IN CITY AREA AND IMPROVEMENT OF VEHICLE FRONT DESIGN FOR PEDESTRIAN IMPACT PROTECTION– A COMPUTER SIMULATION STUDY

Jikuang Yang

Xuejun Liu

Per Lövsund

Crash Safety Division

Chalmers University of Technology, Sweden

Claes Tingvall

Anders Lie

Peter Larsson

Thomas Lekander

Swedish National Road Administration, Sweden

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ABSTRACT

This paper presented a part of results from an ongoing project for pedestrian protection, which is carried out at Chalmers University of Technology in Sweden. A validated pedestrian mathematical model was used in this study to simulate vehicle-pedestrian impacts. A large number of simulations have been carried out with various parameters. The injury-related parameters concerning head, chest, pelvis and lower extremities were calculated to evaluate the effect of impact speed and vehicle front structure on the risk of pedestrian injuries. The effect of following vehicle parameters was studied: stiffness of bumper, hood edge, hood top, windscreen frame, and shape of vehicle front structures. A parameter study was conducted by modeling vehicle-pedestrian impacts with various sizes of cars, mini vans, and light trucks. This choice represents the trends of new vehicle fleet and their frequency of involvement in real world accidents. The mechanical properties of the vehicle front were based on the available data from EURO NCAP tests, and from published literature.

Based on the results from the simulation study, possible benefits from speed control in urban area can be assessed. As the impact speed decreases from the 40 to 30 km/h, the probability of severe head injury will decrease from 50% to lower than 25%.

The influences of the various compliance and geometric parameters of vehicle front are analyzed. The most significant parameters to pedestrian impact protection are clarified, especially for head and lower extremities. A procedure in new vehicle-front design is presented, which can lead to a design guideline of safer vehicles for pedestrians.

Furthermore, gaps in pedestrian protection are identified, and the research priorities should be focused on the adult head and lower extremities and child head and thorax injuries.

INTRODUCTION

Among all road user categories, pedestrians are the most vulnerable road users since they are unprotected in a vehicle impact. Each year thousands of pedestrians are killed or injured in road traffic accidents over the world. Even though the incident of pedestrian fatalities has dropped in most of the highly motorized countries during the past two decades, the number of pedestrian fatalities in road-vehicle accidents is still high. In the European Union (EU) more than 7000 pedestrians are killed each year (EEVC, 1998). The annual pedestrian fatalities vary from about 3000 in Japan, 5500 in the USA (NHTSA, 1998), and 19000 in China (TAPSM, 1997). The proportion of pedestrian fatalities in all killed road users is 18.8% in the EU (ETSC, 1999). Within the EU countries, the relative frequency of the pedestrian fatalities varies remarkably from 14% in Sweden to 32% in UK. Huge economic losses and serious consequences result from these traffic accidents. Pedestrian protection is therefore a priority item in traffic safety strategies (EEVC, 1998; ETSC, 1999). Research into injury mechanisms of pedestrians in vehicle accidents and counter-measures has been widely performed, but little improvement of vehicle for pedestrian safety has been made. There is a need to develop effective safety countermeasures based on knowledge of pedestrian responses and injury mechanisms in vehicle accidents.

Since the 1970's, extensive research has been carried out in the area of pedestrian protection to

determine the causes of accidents and how to avoid them, as well as the causes of injuries and means of reducing them. Many studies on injury mechanisms, tolerance levels, influences of the vehicle design on impact responses, protection assessment techniques, and safety countermeasures have been carried out with pedestrian substitutes such as biological specimens, mechanical dummies and mathematical models (Aldman et al., 1985; Cavallero et al., 1983; Cesari et al., 1994). The impact speed and vehicle front structures including geometry and stiffness have been shown to be important injury-producing factors.

The main factor for measuring the severity of vehicle-pedestrian impacts is the impact speed. In approximately 70% of crashes, the driver braked before the pedestrian was hit (Ashton, 1982; MacLaughlin et al., 1987). Almost 95% of all pedestrian accidents occurred at an impact speed lower than 50 km/h as shown in Figure 1. Pedestrians struck at impact speeds less than 25 km/h usually sustain minor injuries. Serious injuries occur frequently at speeds of 25 to 55 km/h whilst at speeds greater than 55 km/h, pedestrians are most likely to be killed (Ashton, 1982).

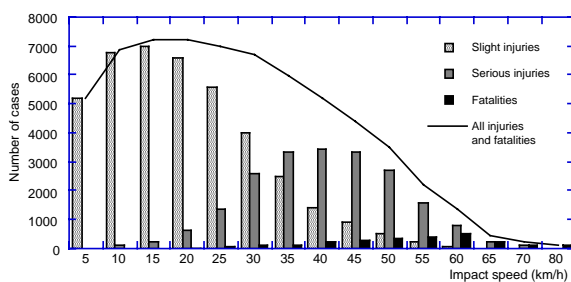


Figure 1. The injury severity distribution as a function of impact speed (based on Ashton, 1982).

Pedestrians were primarily impacted by the car front with a high frequency in car-pedestrian accidents. The European Experimental Vehicle Committee (EEVC) has therefore proposed test procedures to evaluate the fronts of passenger cars for pedestrian safety (EEVC, 1998). The EEVC proposal recommend impact tests to the car fronts with subsystem impactor representing segments of the human body. The subsystem test procedures can be implemented to detect the vehicle front local stiffness and impact energy that are main factors to cause pedestrian injuries.

In order to develop a new vehicle with pedestrian friendly front that can meet the requirements of the subsystem tests it is necessary to have an effective approach for the new vehicle front design to minimize the risk of pedestrian injury in an unavoidable accident. This paper described an approach to investigate the

influences of impact speed and vehicle front structures on pedestrian injuries.

METHOD AND MATERIAL

The approach described in this paper by using mathematical model can be one of phases in a general strategy to find an effective counter-measure for pedestrian protection. The general strategy consists of three phases.

Phase I

The first phase is to develop a global mathematical model that includes system definition, model development and validation.

The system in an accident of pedestrian impacted by a car front consists of exterior parts of car front, road, and pedestrian victims. The elements involved in vehicle-pedestrian impacts can be identified through an in depth study of accident data.

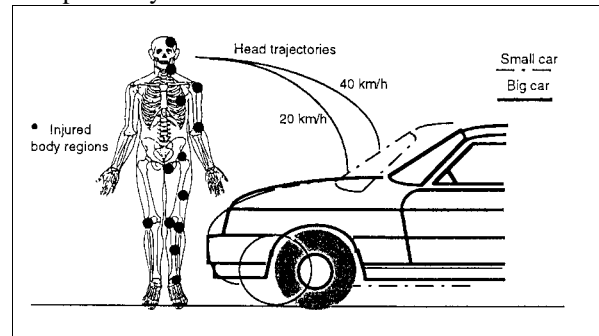


Figure 2. Distribution of injuries to an adult pedestrian in frontal car-pedestrian collisions, trajectories of the head with respect to small and big cars, changes of the locations of the head impact at varying impact speeds.

Figure 2 shows the whole system in a car-pedestrian accident and the distribution of the pedestrian injuries that are influenced by impact speed, car front shape and stiffness, and age, length, size of the pedestrian, as well as standing position of the pedestrian relative to the car.

The Configuration of the Pedestrian Model - A human-body mathematical model was developed at Chalmers University of Technology in Sweden by using MADYMO program (Yang, 1997; Yang et al., 2000). It was validated against impact tests with postmortem human subject (PMHS) and used as a pedestrian substitute for simulation of car-pedestrian impacts (Figure 3). Important injury-related parameters can be calculated by means of the model, including impact forces, accelerations for different body

segments, HIC, transverse dislocation and contact forces between articular surfaces, knee-ligament strain, and knee-bending angle. The leg fracture can be predicted by using a frangible joint defined in the breakable leg segments. It is therefore considered a valuable tool to predict the risk of pedestrian injuries in accidents. The model is also to be used for a parameter study on improvement of vehicle-front design for pedestrian safety.

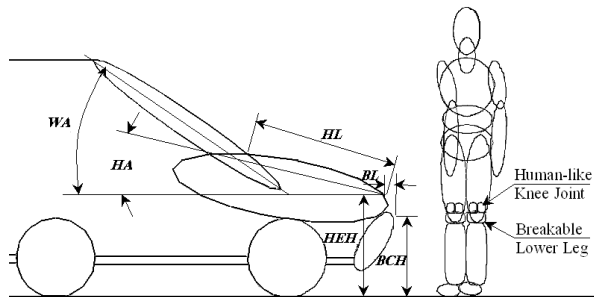


Figure 3. The baseline model set-up for car-pedestrian simulations, BCH=Bumper Central Height, BL=Bumper Lead Length, HEH=Hood-Edge Height, HL=Hood Length, HA=Hood Slope Angle, WA=Windscreen Angle.

The car front model consists of bumper, hood edge, hood top and windscreen as ellipsoids to approximate the exterior profile of vehicle. The four wheels are represented by four identical ellipsoids to produce the braking deceleration of the vehicle by the friction force between wheels and ground. The vehicle model is pitched to provide a geometric attitude equivalent to 0.6g braking. Force-deformation characteristics of car front components are obtained from published data and EURO NCAP tests with headform and legform impactors. The friction coefficient is 0.6 for foot/ground and wheels/ground, 0.5 for contact between body segments and car front structures.

Phase II

The second phase is an early stage design that can begin with evaluation of vehicle-front structures using mathematical model and subsystem tests. The problem with existing vehicle can be identified. This is then followed by optimizing the design and comparing with the original solution to minimize the risk of pedestrian injuries. The mathematical model developed in the first phase is used for assessment and optimization of vehicle front structure. The important vehicle elements responsible for pedestrian injuries are summarized in Table 1.

With the selected variables of vehicle front, it will cover the vehicle types for small and big size passenger cars, minivan, and light truck (Figure 3).

Definition of the system covers the involved elements in vehicle-pedestrian accidents and also the determination of the injury related parameters that can be calculated in mathematical modeling (Table 2) and used for evaluation the aggressiveness of the vehicle front parts.

Table 1: The vehicle front parts and variables for parameter study

| Parts | Geometry | Varying stiffness area |
|------------------|--|---|
| Bumper | height lead distance width (in vertical direction) | middle side (bumper assembly point) |
| Bonnet | Front edge height Length Angle | front edge top bonnet fender area |
| Windscreen | Angle | edge |
| Windscreen frame | | A-pillar roof frame |
| Fender | | fender top |

Table 2
Injury related parameters in a lateral loading

| Parameters | Body segments | Tolerance levels |
|----------------|----------------------------------|--|
| Force | tibia knee femur pelvis | 4 kN* 2.5 kN (shear) [4] kN* 4 kN (female)/ 10 kN (male) |
| HIC | adult child | 1000* [1000]* |
| Linear acc | head thorax tibia | 80 g 60 g [150] g* |
| Angular acc | head | [3000] rad/s ² |
| Rotation angle | Knee Neck | 15 degree* [60] degree |
| Bending moment | knee tibia femur | 350 Nm 200 Nm 220 Nm* |
| Translocation | knee | 6 mm* |

* Acceptance levels of EEVC proposal. In [] Data need a confirmation.

Phase III

The third phase, for the design and building of vehicle, consists of choosing the best technological solution, fitting it with optimized definition, and building the prototype. The prototype of the vehicle front structure should be tested to evaluate the validity of the proposed solution.

PARAMETER STUDY

Passenger cars are most frequently involved in vehicle-pedestrian accidents (Ashton, 1982; Otte, 1989; ETSC, 1999). In the EU countries, the number of pedestrians struck by passenger cars is around 60% to 80% of the reported vehicle-pedestrian accidents. In 80 - 90% of the cases the pedestrians were hit from the side. The pedestrians were primarily impacted by the car front with a frequency of 80%. Therefore a parameter study was carried out with selected car front variables. To evaluate the injury risks of pedestrians at different impact speeds, it's desirable to take into account of the distributions of the different vehicle types involved in pedestrian injury accidents. Therefore four vehicle types have been simulated in this study, as described in Table 5 (APPENDIX).

The parametric study involving various variables such as impact speed, vehicle front shapes and compliance properties is conducted with the validated pedestrian mathematical model (Yang, 1997; Yang *et al.*, 2000).

Design of Parametric Study

In present study the parametric study has been divided into three parts. The first part concerns the influence of impact speed, taking into account of involvement of different vehicle models including large and compact passenger car, mini van and light trucks. The main purpose is to predict the effect of impact speed on the injury risk of pedestrian exposed to the real world traffic accidents. The injury patterns with regard to different vehicle models will also be compared. Secondly, the effects of variations of several vehicle front shape parameters on the impact severity of pedestrian will be discussed with passenger car models at impact speed of 40 km/h. It is aimed to reveal the possible improvement of vehicle shape to mitigate the injury severity of pedestrian. Finally the influence of force-deformation properties of vehicle structure will be discussed at impact speed of 40 km/h.

The four levels of impact speed are presented in Table 3. The selected geometric and stiffness variables and corresponding levels are listed in Table 4.

Bumper central height are chosen between knee joint and center of gravity of the lower leg for a 50th percentile adult male. The hood edge height varies between hip and knee joint. The hood length are varied at three levels in order to simulate the different vehicle types, of which 1200 mm for large passenger car, 700 mm for compact passenger car and 500 mm for van and light trucks. Hood slope angle also depends on the specific vehicle models. For instance, hood slope angle at 10 degree is assigned for passenger cars, whereas 30 degree for mini van and 45 degree for light truck. Likewise, windshield angle is also varied to fit the different vehicle models. In the case of mini van and small passenger car, windshield angle has two levels at 30 and 45 degree. For large passenger car and light truck, the windshield angle is 30 and 45 degree respectively. These dimensions are defined in Figure 3. By varying the bumper height, bumper lead, hood edge height, hood length and slope angle, and windshield angle, different vehicle models and front shapes can be simulated, as listed in Table 5 (APPENDIX).

Table 3. Selected levels of vehicle impact speed

| Impact Speed | Levels (km/h) | | | |
|--------------|---------------|----|----|----|
| | 20 | 30 | 40 | 50 |

Table 4. Selected Factors and levels for parameter study

| Geometric and Stiffness Factors | Levels | | |
|----------------------------------|--------|-----|------|
| | -1 | 0 | +1 |
| BCH= Bumper Central Height (mm) | 300 | 400 | 500 |
| BS = Bumper Stiffness (N/mm) | 125 | 250 | 500 |
| BL = Bumper Lead (mm) | 50 | 100 | 200 |
| HEH= Hood Edge Height (mm) | 600 | 700 | 800 |
| HES= Hood Edge Stiffness (N/mm) | 200 | 400 | 800 |
| HL = Hood Length (mm) | 500 | 700 | 1200 |
| HTS= Hood Top Stiffness (N/mm) | 75 | 150 | 300 |
| HA = Hood Slope Angle (deg) | 10 | 25 | 45 |
| WA = Windshield Angle (deg) | - | 30 | 45 |
| WS = Windshield Stiffness (N/mm) | 300 | 600 | 800 |

The medium level of force-deformation properties for different structures are consistent with the input data of validation simulation (Yang, 2000). Some of the data, such as bumper, and hood top are obtained from EURO NCAP subsystem tests according to the test procedures proposed by EEVC (1994 and 1998). Hood edge stiffness is estimated within the corridor reported by Ishikawa (1991). All these stiffness variables vary from 50% to 200% to simulate the different impact locations on vehicle front structure.

Simulation Matrix

Table 5 (APPENDIX) shows the simulation matrix, which is based on the involvement of different vehicle models (NHTSA, 1998), of which large and compact passenger car has 9 samples for each (56% in

total), whereas Van/Utilities (17%) and Light Trucks (17%) has 6 samples for each.

Since hood edge height and bumper center height have been recognized as two key factors affecting the pedestrian overall kinematics and the injury severity to knee joints. These two variables are varied in full factorial of three levels, which lead to 9 variations for both large and compact passenger cars as shown in Table 5. Other variables vary in reverse levels for large and compact passenger car, so that the corresponding effects can be obtained through these two blocks. The geometric and stiffness variables for van and light truck only vary in two levels due to the obvious higher and stiffer front profile than passenger cars. The effects of variables calculated from van and light truck models serve as a complementary to that from passenger cars.

The influences of geometric variables of vehicle front end on pedestrian responses are evaluated with the basic configuration of large passenger car at impact speed of 40 km/h. The stiffness variables remain constant at their middle levels as below:

- bumper stiffness: 250 N/mm
- hood lead edge stiffness: 400 N/mm
- hood top stiffness: 150 N/mm
- windscreen stiffness: 600 N/mm

The geometric variables including bumper center height, bumper lead length, and hood edge height vary at three levels, which makes 27 runs in full factorial analysis.

Similarly, the effects of different stiffness variables on pedestrian injuries are studied at impact speed of 40 km/h with a certain vehicle front shape as follows:

- bumper center height: 400 mm
- bumper lead length: 100 mm
- hood lead edge height: 700 N/mm
- hood length: 1200 mm
- hood slope angle: 10 degree
- windscreen slope angle: 30 degree

To avoid the interference of windscreen to the pedestrian kinematics, the hood length is chosen at the upper level of 1200mm. While the windscreen stiffness remains constant, other three stiffness variables including bumper stiffness, hood edge stiffness and hood top stiffness are varied according to three-level full factorial design, leading to 27 runs totally. The effects of specific variables and possible interactions on pedestrian injury can be analyzed without any confounding effect between these variables.

Selected Injury Parameters

The injury risk of pedestrian is evaluated in terms of injury parameters and tolerance levels listed in Table 6. Due to the absence of a more appropriate criterion,

the widely accepted HIC (Head Injury Criterion) of 1000 is assigned to predict the resultant head injury. The chest injury criteria - TTI (Thoracic Trauma Index) of 85 g has been proposed as the maximum exposure for adults (NHTSA, 1993). The injury criteria concerning the lower extremities are primarily based on the recent report by EEVC (1998). The thigh impact force of 4 kN represents the 20% AIS2+ injury risk level of femur fracture, whereas tibia acceleration of 150 g indicates 40% risk of an AIS 2+ lower leg fracture. Moreover, a proposed 15 degree of lateral bending angle and 6 mm of knee lateral dislocation serve as the knee joint tolerance levels.

Table 6. Tolerance levels of selected injury parameters

| Injury Parameter | Tolerance Level |
|----------------------------|-----------------|
| HIC | 1000 |
| Chest Acc. (3ms) | 85 g |
| Pelvis Impact Force | 10 kN |
| Thigh Impact Force | 5 kN |
| Tibia Acc. (3ms) | 150 g |
| Knee lateral Dislocation | 6 mm |
| Knee lateral Bending Angle | 15° |

RESULTS

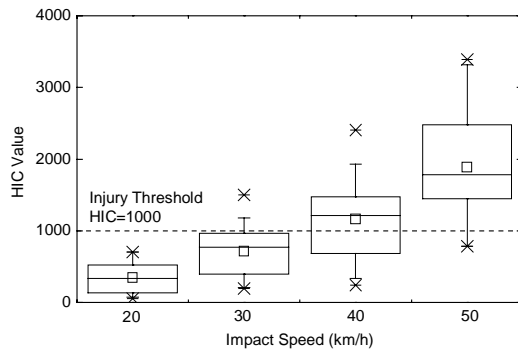
The part of the results is presented here, which was used to evaluate the effects of car-front parameters on the impact force, the knee-rotation angle, the HIC (head injury criterion) value, and head impact speed.

Effect of Impact Speed on Risk of Pedestrian Injuries

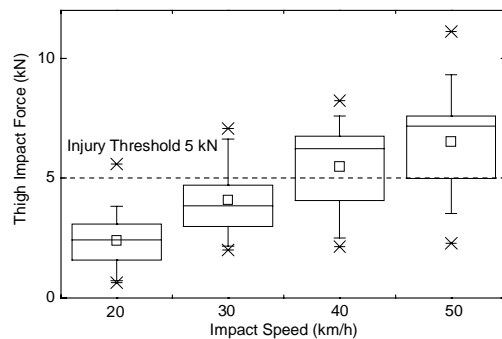
Calculated injury parameters are presented in the form of box diagrams to describe the injury risk of pedestrian at different impact speeds, in which the injury risks are expressed by the probabilities of 25%, 50% and 75% with bottom, medium and top horizontal lines respectively. The effects of different vehicle types with varying front shape and compliance properties are included. From the diagrams in Figure 4, it can be seen that the impact speed has significant influence on all injury-related parameters.

The HIC value increases steadily with the impact speed. The probability of HIC value exceeding 1000 is about 50% at impact speed of 40 km/h, whereas it is lower than 25% at 30 km/h (Figure 4a). The injury risk of thigh exhibits a strong dependency on impact speed. For instance, at impact speed of 30 km/h, there is only less than 25% of all cases exceeding the tolerance level of 5 kN, whereas more than 75% at impact speed of 40 km/h (Figure 4b). The injury risks of knee joint are evaluated by knee lateral bending angle, representing the bending injury mechanism. The knee joint appears

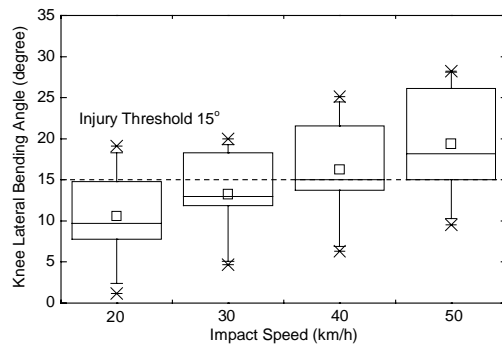
to be the most vulnerable area under the lateral impact loading. Even at impact speed of 20 km/h, the injury risk of knee joint is about 25%, as shown in Figure 4c. As the impact speed increases up to 40 km/h, the injury risk reaches almost 50%.



(a) HIC value.



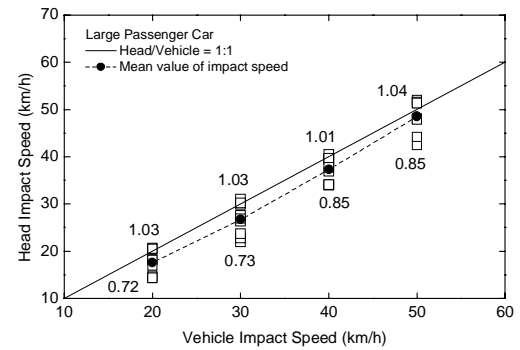
(b) Thigh impact force.



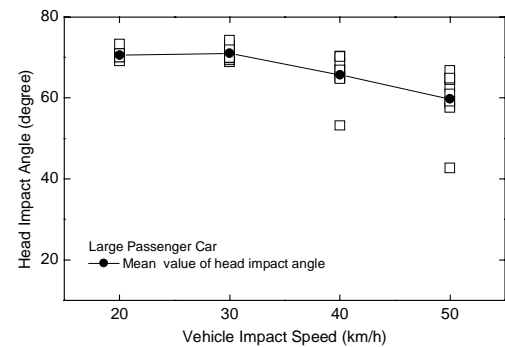
(c) Knee lateral bending angle.

Figure 4. The injury risks at different impact speeds.

Figure 5 describes the dependency of head impact speed and angle on vehicle travel speed. These two items are the essential test conditions for the head impactor to bonnet top test (EEVC, 1998). It's clearly that head impact speed increases proportional with the vehicle impact speed. The head impact angle varies from 42 to 73 degree for large passenger car.



(a) Head impact speed for large passenger car.



(b) Head impact angle for large passenger car

Figure 5. The influence of vehicle impact speed on head impact speed and angle

The considerable variations in calculated injury parameters at a given impact speed imply that factors other than impact speed are also important in determining the injury severity of pedestrians. Therefore, an intensive analysis involving geometric and stiffness variables are conducted to reveal the corresponded effects on pedestrian injury severity.

Effect of vehicle front structure on impact responses of pedestrians

Vehicle Types - The resultant head velocities are greatly affected by the vehicle types as shown in Figure 6. In case of the light truck, resultant head velocity approximately remains constant during the first 50 ms after the initial impact, and then decreases sharply after the head impact with windshield structure at 10.0 m/s (55ms), slightly lower than the travel speed of vehicle (11.11 m/s). For the mini van and passenger cars, the resultant head velocities increase progressively and reach the maximum at around 13.1 and 13.9 m/s, respectively. The actual head impact speed against vehicle structure varies from 10.8 m/s (95 ms) for mini van, 13.1 m/s (105 ms) for compact passenger car to 10.2 m/s (116 ms) for large passenger car.

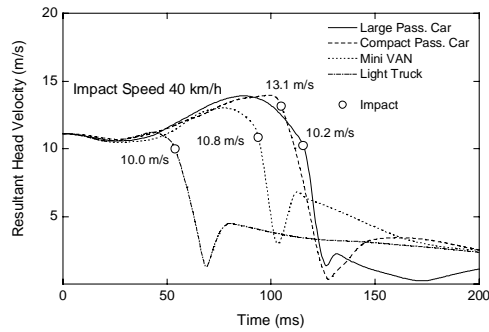


Figure 6. Resultant head velocity against different vehicle types at 40 km/h.

The differences in head velocity changes can be mainly attributed to the different hood slope angles (Table 7) of various vehicle types, which lead to different kinematics of pedestrian after the initial contact with bumper. Due to the large hood slope angle of light truck, the pelvis and chest contact with hood earlier than mini van and passenger cars. Consequently the pedestrian body has not been rotated but pushed forward along the direction of vehicle travel speed. When impacted by mini van or passenger cars, the pedestrian body is rotated downwards to the hood top, leading to a considerably rotational movement after the impact. The resultant head velocities thus increase after initial impact for both mini van and passenger cars. The extent of this rotational movement differs with the slope angle and length of hood. Compared to the large passenger car, the moment of head impact is earlier for compact passenger car, which results in higher head impact speed accordingly.

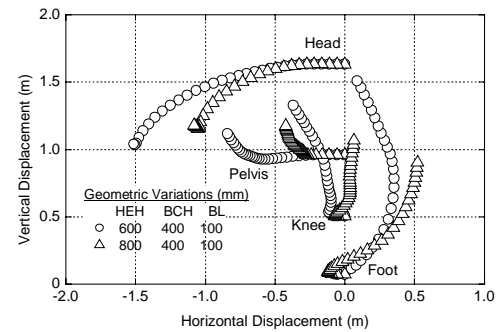
Table 7. Comparison of injury parameters with different vehicle types at 40 km/h

| Injury Parameters | Vehicle Types | | | |
|-------------------------|---------------|-----------|----------|-------------|
| | Large Car | Comp. Car | Mini Van | Light Truck |
| HIC | 890 | 514 | 1261 | 1317 |
| Chest Acc. (3ms-g) | 24 | 27 | 45 | 59 |
| Pelvis Impact Force(kN) | 5 | 2.8 | 6.7 | 7.3 |
| Thigh Impact Force (kN) | 6.7 | 3.6 | 5.8 | 6.2 |
| Knee Lateral Angle(deg) | 25 | 12 | 20 | 20 |
| Knee Lateral Disl. (mm) | 5.1 | 8.6 | 5.0 | 5.0 |

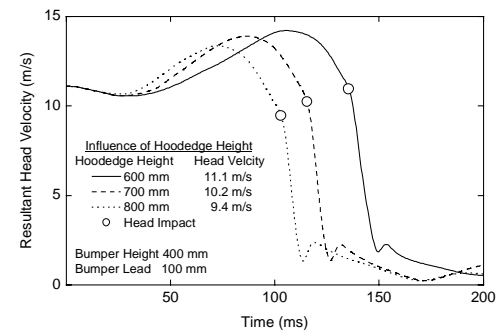
Table 7 summaries the mean values of various injury parameters at impact speed of 40 km/h with respect to different vehicle types. In the simulation with van and light truck model, the contact locations of pedestrian head are closed to the lower windshield frame, where is stiffer than the center of windshield and hood top. Therefore high injury risk of head has been found in terms of HIC value. Moreover, large hood slope angle results in the direct blow on pedestrian chest and pelvis area, the injury risk to these body parts are higher than that of passenger cars with apparent 'slipping' movement along hood top. The

injury risks to lower extremity of different vehicle types are compared in terms of thigh impact force and knee joint injury risk. Generally, pedestrian is exposed to high injury risk to upper body area against the mini van and light truck, while the passenger cars are more aggressive to the lower extremity. Similar tendency has been found in pedestrian accidents (Mizuno *et al.*, 2000).

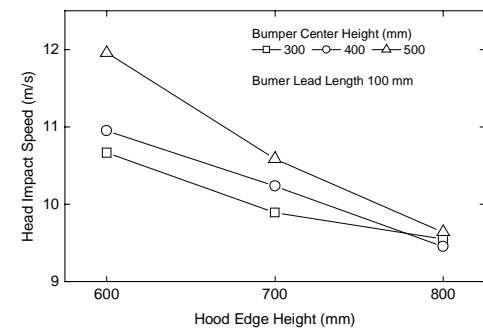
Vehicle Front Shape - To avoid the effects of hood slope angle and hood length on pedestrian kinematics, only large passenger cars are considered to assess the influences of bumper center height, bumper lead length and hood edge on head and lower extremity injuries.



(a) Influence of hood edge height on pedestrian kinematics.



(b) Influence of hood edge height on resultant head velocity



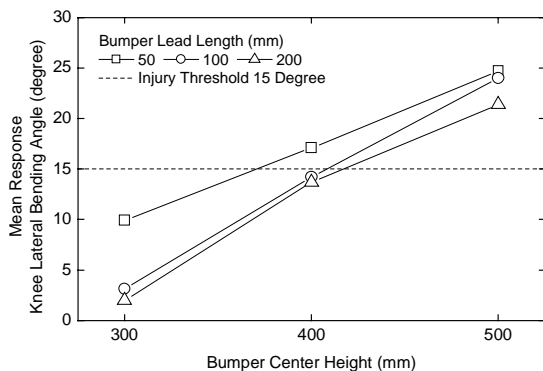
(c) Interaction between bumper height and hood edge height on head impact speed.

Figure 7. Influence of vehicle front shape parameters on pedestrian kinematics and head responses.

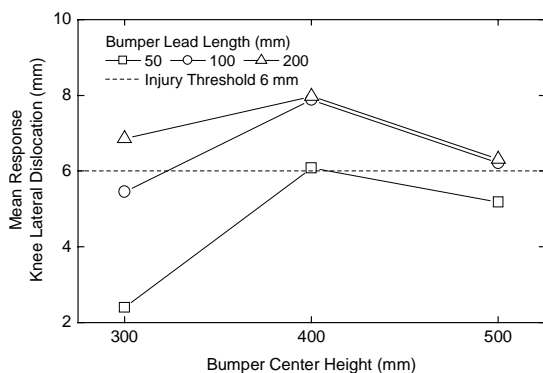
Clearly, hood edge height has great effect on pedestrian kinematics and resultant head velocity. When hood edge height varies from 800 to 600 mm, the WAD (Wrap Around Distance) increases from 1.78 m to 2.05 m, due to the considerable 'slipping' effect of pedestrian body, as shown in Figure 7a. The head impact speed increases from 9.4 m/s to 11.1 ms/s (Figure 7b).

The main effect of hood edge height, and interaction between bumper center height and bumper lead length on head impact speed are described in Figure 7c. It's clearly that hood edge height has greater effect than other two parameters. No significant interaction exists between hood edge height and bumper center height, as shown in Figure 7c.

In general, the head impact speed tends to decrease with an increase of hood edge height and a lowering of bumper center height, but has little relation to bumper lead length.



(a) Interaction between bumper center height and bumper lead length on knee lateral bending angle



(b) Interaction between bumper center height and bumper lead length on knee lateral dislocation

Figure 8. Influence of vehicle front shape on knee joint injuries.

The influences of the vehicle shape variables on knee joint injuries are described in Figure 8, in which

the possible interactions among bumper center height, bumper lead length and hood edge height were also presented.

The results indicate that lowering bumper center height is favorable to reduce the knee lateral-bending angle (Figure 8a). For instance, when the bumper center height decreases from 500 to 300 mm (nearer the center of gravity of the lower leg) the knee lateral bending angle was reduced by 67% (15 degree to 5 degree).

However, the knee lateral dislocation is dependent on both bumper center height and bumper lead length (Figure 8b). As the bumper height decreases from 500 to 400 mm in case of bumper lead length of 50 mm, the knee lateral dislocation increased from 5.2 to 6.1 mm. When the bumper center height decreases further to 300 mm, the knee lateral dislocation decreases to 2.4 mm.

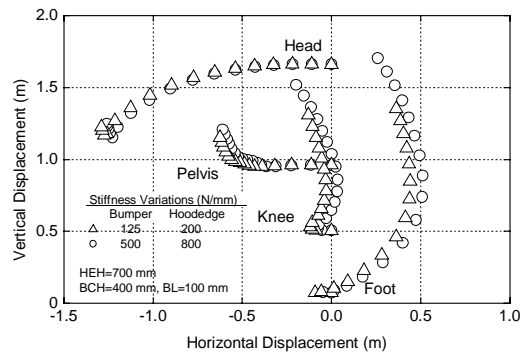
No significant interaction exists between bumper center height and hood edge height in terms of knee injury parameters. Therefore, it can be concluded that the hood edge height has little effect on both knee lateral-bending angle and lateral dislocation. This result was consistent with the previous studies conducted with mechanical substitutes and computer simulation (Ishikawa *et al.*, 1994; Nagatomi *et al.*, 1996).

Influence of Vehicle Stiffness Properties The influence of vehicle stiffness properties is analyzed in terms of pedestrian kinematics, resultant head velocity and injuries to head and lower extremity regions.

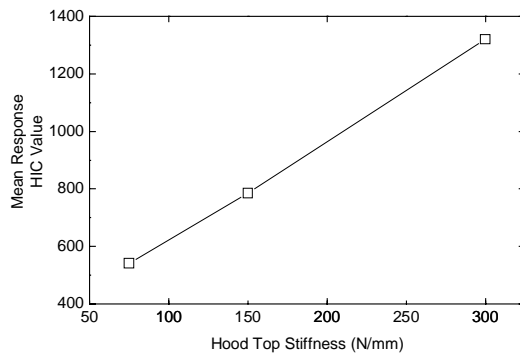
Figure 9a shows the influence of stiffness variations of bumper and hood edge on pedestrian kinematics. Although the stiffness varies between 50% and 200%, there is slight effect on head trajectory and speed.

Figure 9b illustrates influence of local stiffness of contact area on the injury severity of different body segment. It is clearly that the stiffness variables have significant effects on head and lower extremity injuries, with the given vehicle front shape and impact speed. As shown in Figure 9b, a soft hood top can provide a significant protection performance to head injury severity, compared with other two levels of hood top stiffness. Similar tendency is also found in terms of thigh (Figure 9c), knee joint (Figure 9d) injury severity.

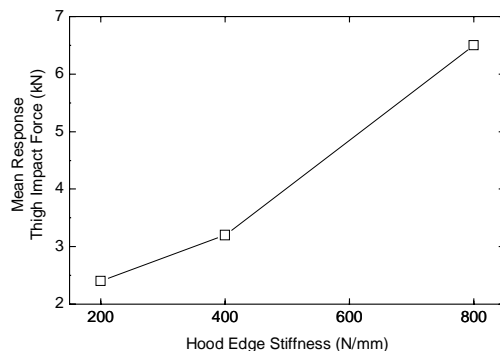
Compared with the influence of vehicle shape variables, stiffness proprieties have great effect on resulted injury severity, but minor influence on pedestrian gross motion.



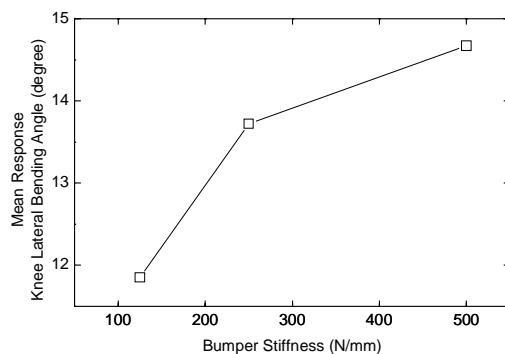
(a) Influence of stiffness properties on pedestrian kinematics,



(b) Influence of hood top stiffness on HIC value



(c) Influence of hood edge stiffness on thigh impact force.



(d) Influence of bumper stiffness on knee bending angle.

Figure 9. Influence and interactions of vehicle front stiffness variables on lower extremity injuries

DISCUSSION

The influences of impact speed, vehicle front shape and compliance on pedestrian responses are evaluated in terms of the calculated injury parameters. The mean values of injury parameters are plotted in terms of different geometric and stiffness parameters. The main effects of these variables and possible interactions are examined.

The results from parameter study indicated the significant effects of the bumper height, bumper stiffness, bumper-lead distance, and hood-edge height on responses of the knee-leg complex in a lateral impact to the leg. The head responses appear to be dependent primarily on hood-edge height. Injury to the lower extremities and head is influenced by car front parameters. Thus it is necessary to perform an optimization study on new car front design.

The tendency of reduction of the pedestrian fatalities during past years is mainly due to improved traffic planning in built-up areas. New aerodynamic car designs may also have contributed to the reduction of pedestrian injury. The modern cars with new aerodynamic design have changes in front-end shape by rounded bonnet edges, smooth surfaces and a low bumper which is in accordance with the principle of an improved car design for pedestrian protection. The findings from experimental studies (Ashton, 1982; NHTSA, 1993; EEVC, 1998; ETSC, 1999) suggest that a potential benefit could be obtained from changes in car front-end.

Effective counter-measures require knowledge about pedestrian injuries and injury mechanisms in accidents. Knowledge about injury mechanisms of pedestrians in car impacts has mainly been achieved from tests with PMHS. PMHS tests, however, can not be used for extensive study of safety counter-measures due to ethical problems and high cost of such tests. Several types of pedestrian dummies have therefore been developed to evaluate new counter-measures. So far none of them have been found appropriate to simulate responses of pedestrians in car impacts due to biofidelity and repeatability problems. The subsystem test procedure is an important measure to determine the aggressiveness of car front parts in pedestrian accidents. The kinematics in car-pedestrian impacts are quite complex due to successive impacts to the body segments in a large relative movement between pedestrian and moving car front. There is a need of a validated pedestrian mathematical model that can be used for the prediction of the kinematics behavior and injury risks of pedestrians as well as for the evaluation of safety concepts in the early stages of car designs.

Improving pedestrian protection via new vehicle front design

A general principle for pedestrian protection is to reduce local stiffness of the car-front components and minimize impact energy in collisions. It could be implemented by using energy-absorbing materials, removing sharp edges and increasing the distance between the bonnet and engine components, as well as spreading impact forces over as wide a body area as possible and preferably over the strongest skeletal structure. Modifying the construction of the bonnet, especially the rear part of the bonnet and bonnet-fender regions, and the under-bonnet clearance provides head impact protection. Lowering the bumper height to a suitable level and increasing the compliance and width of the bumper system can reduce risk of leg and knee injuries.

Pedestrians may also benefit from other crash safety strategy such as automatic radar braking systems, which can detect the presence of an object in the path of a car and automatically brake a car to a lower speed.

The third phase in proposed procedure for research into pedestrian protection have not yet implemented in the present study. It can be conducted with the findings from the parameter study by developing a prototype of pedestrian friendly vehicle. As a positive effect to pedestrian safety, a pedestrian friendly vehicle can minimize the risks of pedestrian injuries in combination with suitable speed limit in city build up area.

CONCLUSIONS

- The validated pedestrian model based on human body characteristics is an effective means to study the complex collision event between vehicle structure and human body. The results from parametric study have indicated that the injury severity of pedestrian is strongly affected by impact speed and vehicle design, and can be greatly reduced by altering vehicle front shape and structure stiffness properties.
- Impact speed has the critical significant effect on the pedestrian injury severity. As the impact speed decreases from 40 to 30 km/h, the probability of severe head injury ($HIC > 1000$) will decrease from 50% to lower than 25%, whereas the injury risks to knee joints remains above 50%. Considering the possible improvement of vehicle front structure to mitigate the injury severity to knee joint, it is concluded that a speed limit of 30 km/h in urban area is effective means to reduce the pedestrian injury risk.

- The kinematics and injury patterns of pedestrian vary considerably with the vehicle models. For van or light truck, the translational movement of pedestrian body determines the injury patterns and distributions, whereas rotational movement is significant for the passenger cars. Consequently pedestrian is exposed to high injury risk to upper body area against the mini van and light truck, while the passenger cars are more aggressive to the lower extremity than mini van and light truck.
- As to the kinematics and resultant head velocity of pedestrian struck by passenger cars, hood edge height has been identified as the dominant factor. The effect of bumper center height and bumper lead length is slight. In general, head impact speed decreases with an increase of hood edge height and a lowering bumper center height.
- The injury severity to the knee joint is strongly influenced by the bumper central height and stiffness properties. Bumper lead and hood edge height only has slight effect on lateral bending angle of knee.
- The local stiffness of head contact area greatly controls the resulting injury severity of head. The influence of force-deformation properties of bumper and hood edge on pedestrian kinematics and head impact speed is slight, but significant for the resulting injury severity to the involved body segments.

Further research is to be focused on:

- Development of a series of pedestrian models that cover different ages of child pedestrian groups and to be used for study on child pedestrian protection.
- The protection priorities of child head/neck/thorax injuries, adult head/neck injuries, as well as leg and knee injuries.
- Development of a prototype of pedestrian friendly car based on findings from parameter study.
- Possible speed limit in city area considering a vehicle fleet designed for pedestrian protection.

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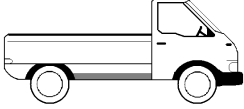
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APPENDIX

Table 5. Simulation matrix for influence of impact speed

| Vehicle Types | BCH | BS | BL | HEH | HES | HTS | WA | WS |
|--|-----|----|----|-----|-----|-----|----|----|
| Large Passenger Car HL= 1.2 m, HA= 10 ⁰ WA=25 ⁰  | -1 | 1 | 1 | -1 | 1 | 1 | 0 | 1 |
| | 0 | 0 | 0 | -1 | 0 | 0 | 0 | 0 |
| | 1 | -1 | -1 | -1 | -1 | -1 | 0 | -1 |
| | -1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | -1 | -1 | 0 | -1 | -1 | 0 | -1 |
| | -1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| | 1 | -1 | -1 | 1 | -1 | -1 | 0 | -1 |
| Compact Passenger Car HL=0.7 m ,HA=10 ⁰  | -1 | -1 | -1 | -1 | -1 | -1 | 1 | -1 |
| | 0 | 0 | 0 | -1 | 0 | 0 | 0 | 0 |
| | 1 | 1 | 1 | -1 | 1 | 1 | 1 | 1 |
| | -1 | -1 | -1 | 0 | -1 | -1 | 0 | -1 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| | -1 | -1 | -1 | 1 | -1 | -1 | 1 | -1 |
| | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Van/Utilities HL=0.5m, HA=30 ⁰  | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |
| | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 |
| Light Truck HL=0.5 m, HA=45 ⁰  | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |
| | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 |
| | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |